# *Hidden sector searches at $e^+e^-$ colliders*

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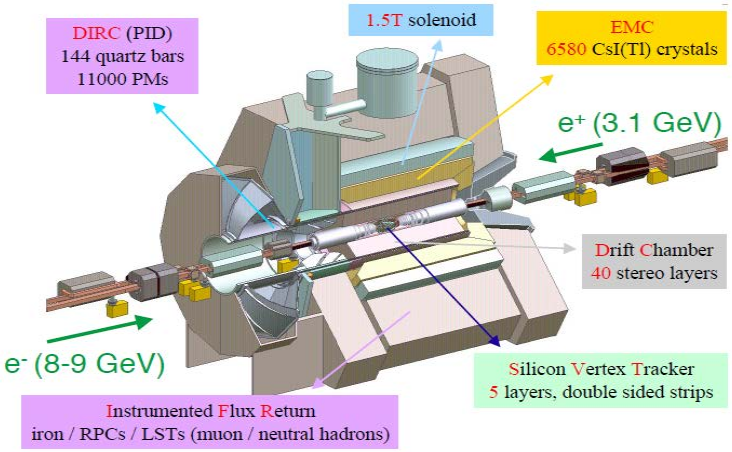
**California Institute of Technology**

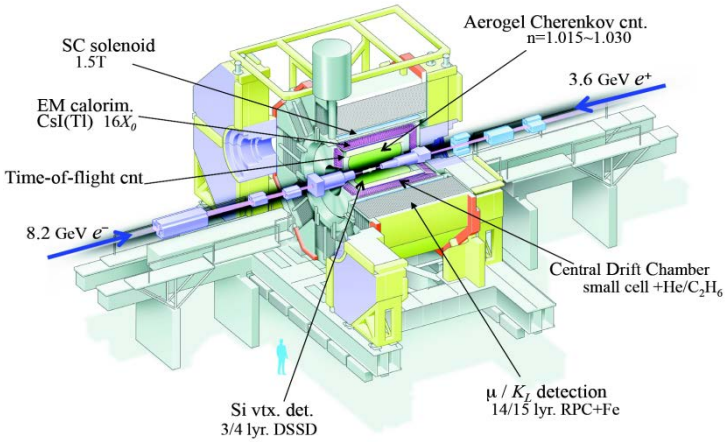
**Snowmass 2013**
**Minneapolis– August 2013**

**BABAR / Belle collected around 550 / 1000 fb$^{-1}$ of $e^+e^-$ data around the Υ(4S) resonance**

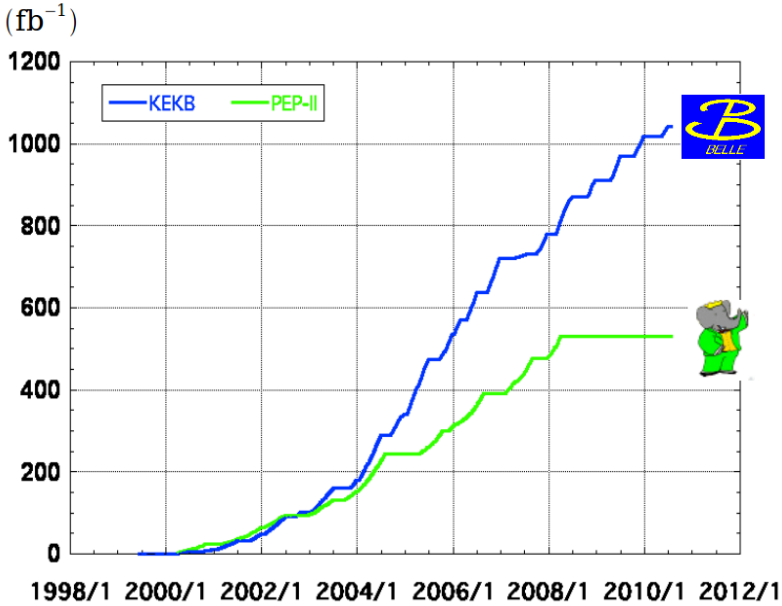
## BABAR detector




## Belle detector




## Integrated luminosity of B factories

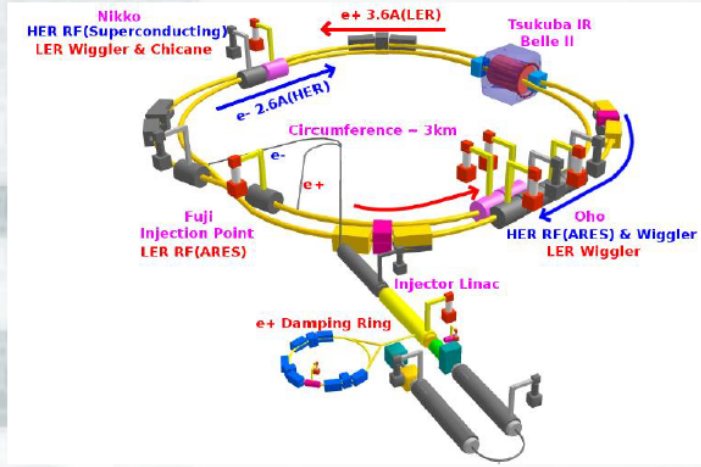


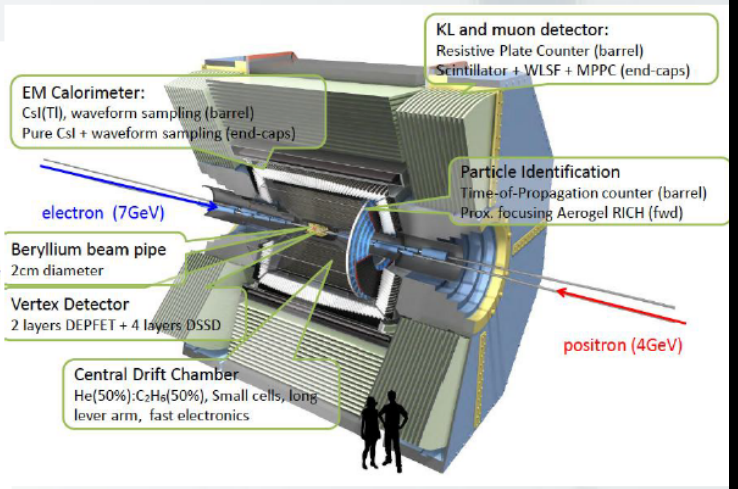

**> 1 ab$^{-1}$**
**On resonance:**
Υ(5S): 121 fb$^{-1}$
Υ(4S): 711 fb$^{-1}$
Υ(3S): 3 fb$^{-1}$
Υ(2S): 25 fb$^{-1}$
Υ(1S): 6 fb$^{-1}$
**Off reson./scan:**
~ 100 fb$^{-1}$

**~ 550 fb$^{-1}$**
**On resonance:**
Υ(4S): 433 fb$^{-1}$
Υ(3S): 30 fb$^{-1}$
Υ(2S): 14 fb$^{-1}$
**Off resonance:**
~ 54 fb$^{-1}$

# SuperKEKB/Belle II

K. Hayasaka




| | KEKB | | superKEKB | |
|---|---|---|---|---|
| Vertical β function: | 5.9 mm | → | 0.27/0.30 mm | (x20) |
| Beam current: | 1.7/1.4 A | → | 3.6/2.6 A | (x2) |

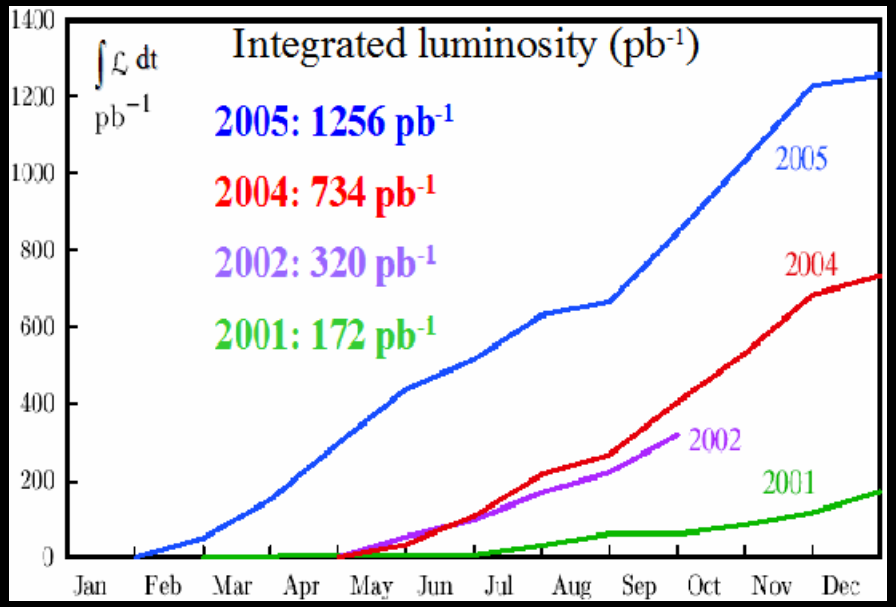
→ $L = 2\times10^{34}\ cm^{-2}s^{-1} \rightarrow 8\times10^{35}\ cm^{-2}s^{-1}$ (x40)

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Should collect about 50 $ab^{-1}$ by 2022 (x100 *BABAR* data)
→ improve by factor 10-100 current analysis at B-factories depending on background and detector performance

# KLOE and KLOE-II experiments

KLOE collected around 2.5 $fb^{-1}$ of $e^+e^-$ data around the $\phi$ resonance




KLOE-II has for objective to increase by an order of magnitude the dataset collected by KLOE with an upgraded detector

→ sensitivity should increase by a factor 3-5 w.r.t KLOE

M. E. Biagini

# Super τ/charm proposals

| | Italian Tau/Charm | BINP Tau/Charm | IHEP Tau/Charm | Turkish Charm |
|---|---|---|---|---|
| | 2 rings | 2 rings | 2 rings | Linac+ring |
| Luminosity ($cm^{-2}s^{-1}$) | $1 \times 10^{35}$ | $1 \times 10^{35}$ | $1 \times 10^{35}$ | $1.4 \times 10^{35}$ |
| Circumference (m) | 340 | 360/800 | 990 | 250 (600?) |
| Beam energy (GeV) | 1 → 2.3 | 0.5 → 2 | 3 | 1 + 3.56 |
| Emittance H (nm) | 5 | 3/10 | 10 | 16 |
| Coupling (%) | 0.25 | 0.5 | 0.5 | 0.3 |
| IP β (x,y) (mm) | 70, 0.6 | 200,0.6/20, 0.76 | 1000, 1 | 80, 5 |
| bb V tune shift | 0.64 → 0.08 | 0.095→0.17 | 0.06 | 0.12 |
| Crab waist | YES | YES | YES | NO |
| Beam current (A) | 1 → 1.7 | 1.8 → 1.7 | 2.7 | 0.48 + 4.8 |
| N. of bunches | 530 | 418 | 540 | 125 |

Larger cross-section for dark photon production (σ~1/s), but lower luminosity,
→ potential results (very) roughly of the same order of those of Belle II.

# Possible searches at flavor factories

**Search for dark photon**

$e^+e^- \to \gamma A'$ , $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
$e^+e^- \to \gamma A'$ , $A' \to$ invisible

**Search for dark boson(s)**

$e^+e^- \to A'^* \to W' W'$
$e^+e^- \to \gamma A' \to W' W''$

**Search for dark Higgs boson**

$e^+e^- \to h' A'$ , $h' \to A' A'$
$e^+e^- \to h' A'$ , $h' \to$ invisible

**Search for dark hadrons**

$e^+e^- \to \pi_D + X$, $\pi_D \to e^+e^-, \mu^+\mu^-$

**Search for dark photon in meson decay**

$\pi^0 \to \gamma\, l^+l^-$, $\eta \to \gamma\, l^+l^-$ , $\phi \to \eta\, l^+l^-$,...

**Search for dark scalar (s) / pseudoscalar (a)**

$B \to K^{(*)}s \to K^{(*)}\, l^+l^-$
$B \to K^{(*)}a \to K^{(*)}\, l^+l^-$
$B \to ss \to 2(l^+l^-)$
$B \to K\, 2(l^+l^-)$
$B \to 4(l^+l^-)$

**+ related searches (hidden warped extra dimensions,...)**

# Search for dark photon in $e^+e^- \to \gamma A' \to \gamma l^+l^-, \gamma q\bar{q}$

*BABAR*

- $\varepsilon^2$ ~ few $10^{-7}$ – $10^{-6}$ (non-resonant)
- limited trigger efficiency near threshold for $e^+e^-$ channel.

Belle II

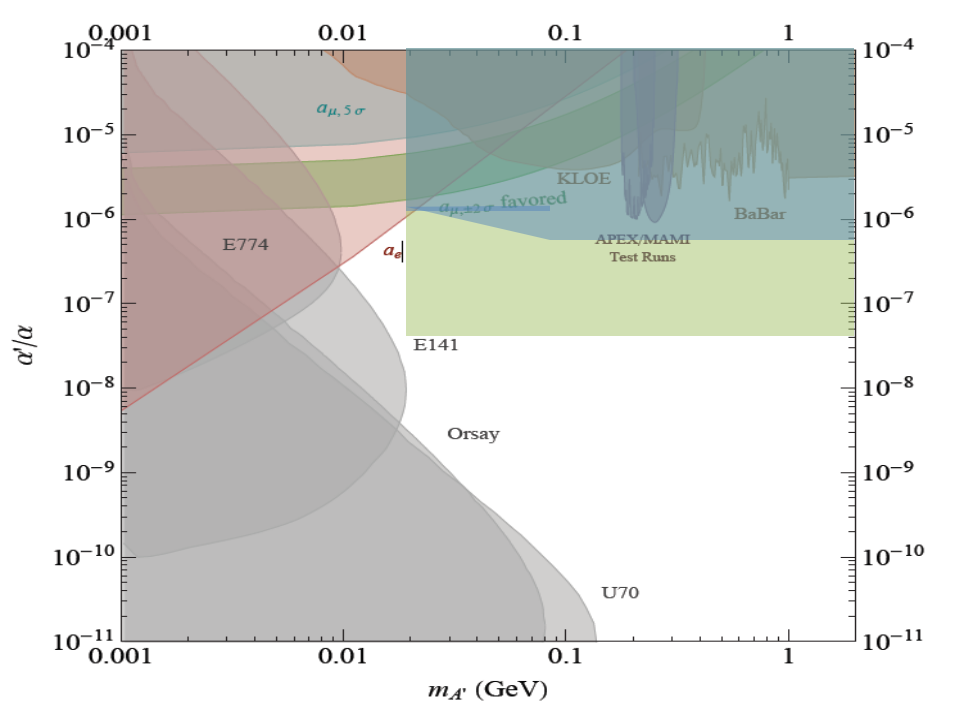
- could improve by factor 10-15 depending on detector performance

Caveat:

- for low masses and low coupling, lifetime becomes large, and background from converted photons becomes a limiting factor. Roughly limited to few $10^{-5}$ / $m_A^2$ (MeV) at B-factories. Should still be ok.

Tried to look at $e^+e^- \to e^+e^- A'$, roughly same sensitivity at *BABAR*.

Projected limits with full *BABAR* dataset for $e^+e^- \to \gamma A'$ , $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$




*BABAR* 500 $fb^{-1}$
Belle II 50 $ab^{-1}$

Only an order of magnitude estimate (ripples not shown)

# Search for dark photon in $e^+e^- \to \gamma A' \to \gamma l^+l^-, \gamma q\bar{q}$

**F. Curciarello**

## U boson searches @ KLOE: $e^+e^- \to \Phi \to U\eta \to e^+e^-\eta$

**Exclusion plot evaluation by using the formula from Reece and Wang, JHEP 07 (2009)**

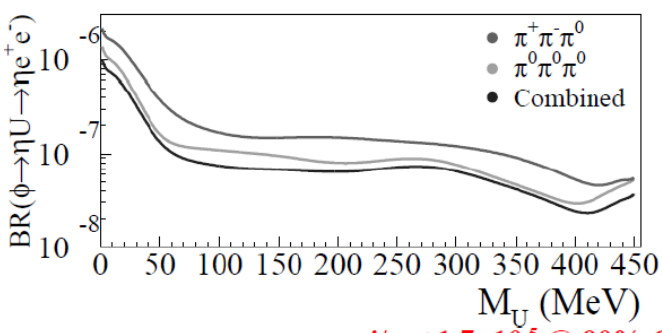
$$\sigma(e^+e^- \to \phi \to \eta U) = \epsilon^2 |F_{\phi\eta}(m_U^2)|^2 \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)} \sigma(e^+e^- \to \phi \to \eta\gamma)$$

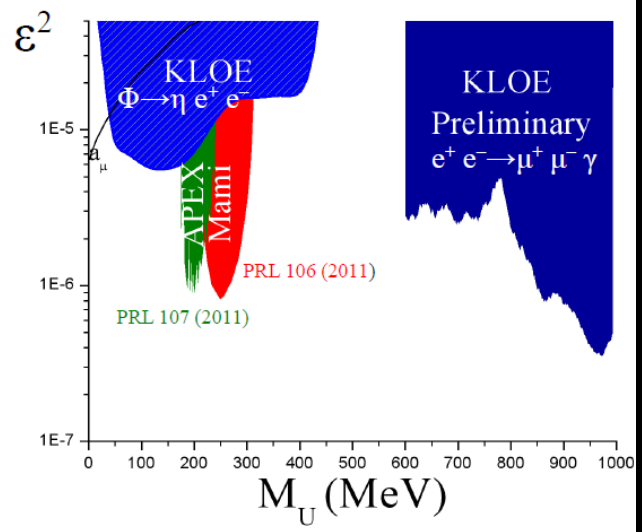
$$\lambda(m_1^2, m_2^2, m_3^2) = [1 + m_3^2/(m_1^2 - m_2^2)]^2 - 4m_1^2 m_3^2/(m_1^2 - m_2^2)^2$$

$$F_{\phi\eta}(q^2) = \frac{1}{1 - q^2/\Lambda^2} \qquad q = M_{ee}$$

FF slope: $\begin{cases} b = dF/dq^2|_{q^2=0} \\ b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} \approx 1/m_\phi^2 \approx 1\ \mathrm{GeV}^{-2} \end{cases}$

VMD




**$\alpha'/\alpha \leq 1.7\times10^{-5}$ @ 90% C.L. For $30 < M_U < 400$ MeV**

**$\alpha'/\alpha \leq 8\times10^{-6}$ @ 90% C.L. for the $50 < M_U < 210$ MeV sub-region**

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Probe down to $10^{-6}$ ($10^{-7}$ in the resonant region) + try to probe very low masses with the $e^+e^-$ final state (new vertex detector)

# *Search for invisible dark photon decay*

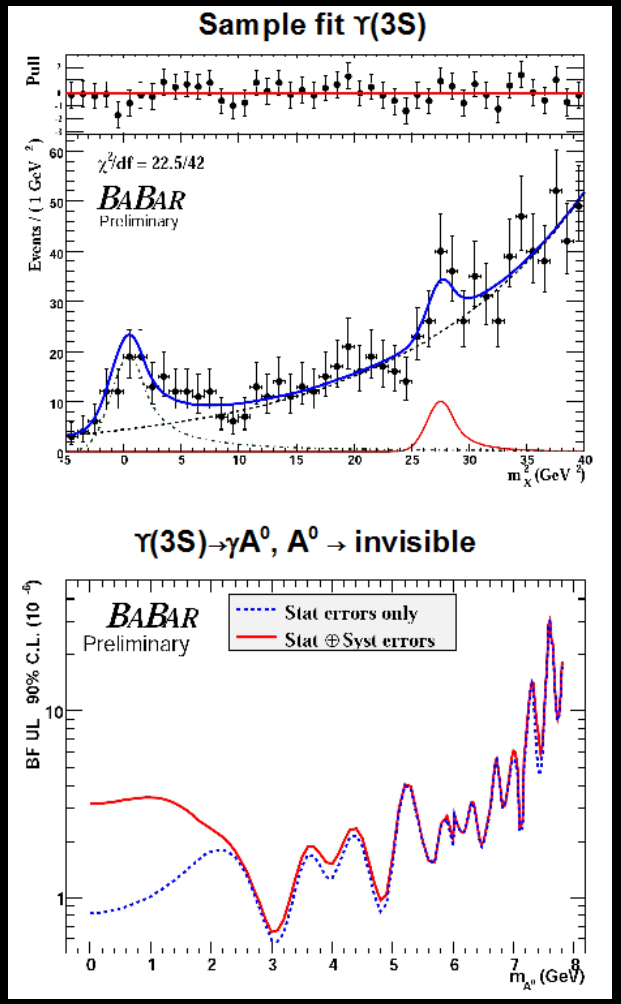
arxiv:0808.0017

Several scenarios with dark photon decay to invisible particles. Dark photon or similar particle may be long lived and escape detector, or dark photon decays to lighter dark states.

Current measurement of
$\Upsilon(2S,3S) \rightarrow \gamma$ + invisible at *BABAR*
could be extended to the dark photon case, limits on $\varepsilon^2$ should be at the level of $10^{-6}$ - $10^{-5}$.

Background from $e^+e^- \rightarrow \gamma\gamma$ becomes a limiting factor at low masses.

**$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible**, new analysis in progress + extension to A'



# Search for invisible dark photon decay

arXiv:1211.2258

Several scenarios with dark photon decay to invisible particles. Dark photon or similar particle may be long lived and escape detector, or dark photon decay to lighter dark states.

Current measurement of $\Upsilon(2S,3S) \rightarrow \gamma$ + invisible at *BABAR* could be extended to the dark photon case, limits on $\varepsilon^2$ should be at the level of $10^{-6}$ - $10^{-5}$.

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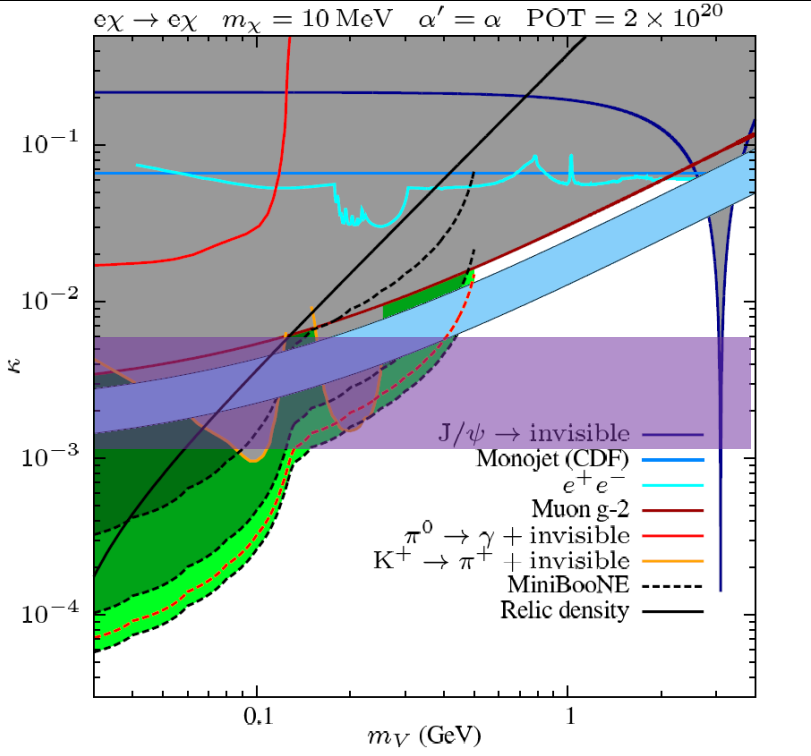



Potential at Belle II depends on the detector performance and the trigger configuration (need single photon trigger). Could potentially improve limits on $\varepsilon^2$ up to a factor ~30, but the low mass region might be background limited and provide little improvement.

Complementary to proton beam dump experiments

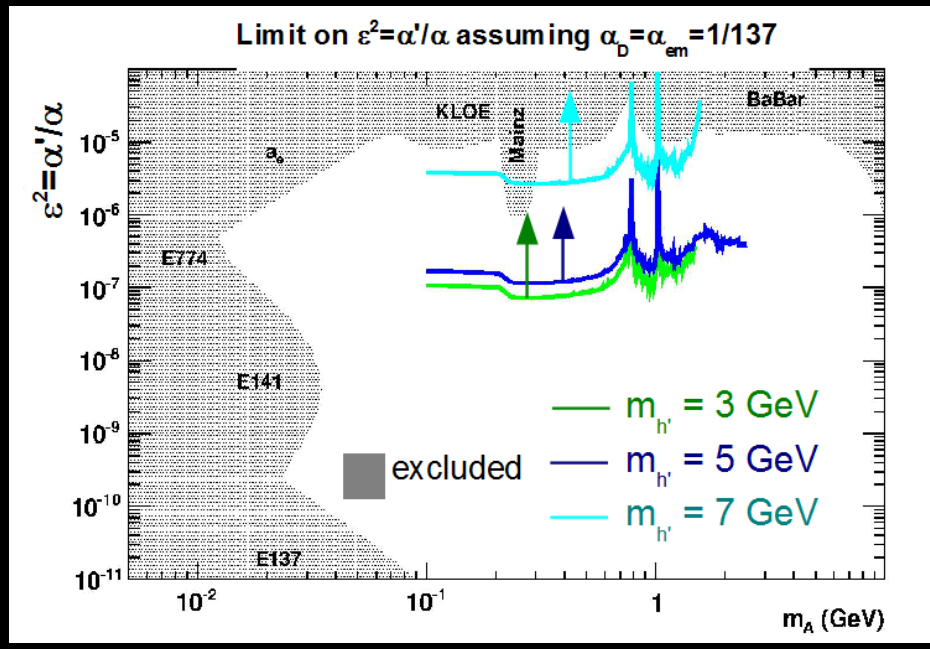
# Search for dark Higgs boson

*PRL 108 (2012) 211801*

- Dark photon mass is generated via the Higgs mechanism, adding a dark Higgs boson (h')
- A minimal scenario has a single dark photon and a single dark Higgs boson.
- The Higgsstrahlung process

$$e^+e^- \rightarrow A'^* \rightarrow h' A' \,,\; h' \rightarrow A' A'$$

- is very interesting, as it is only suppressed by $\varepsilon^2$ and is expected to have a very small background.



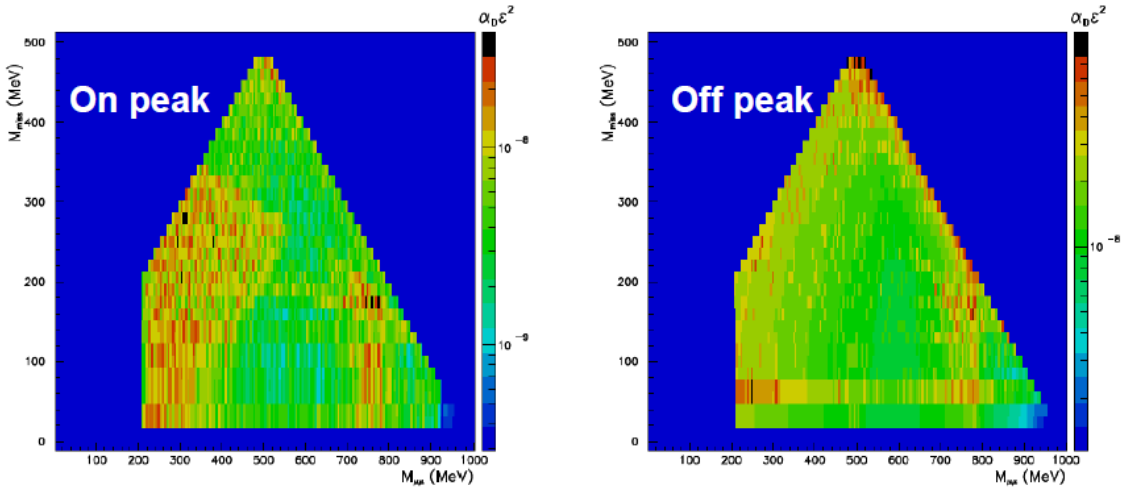

On-going Belle analysis, roughly same limits

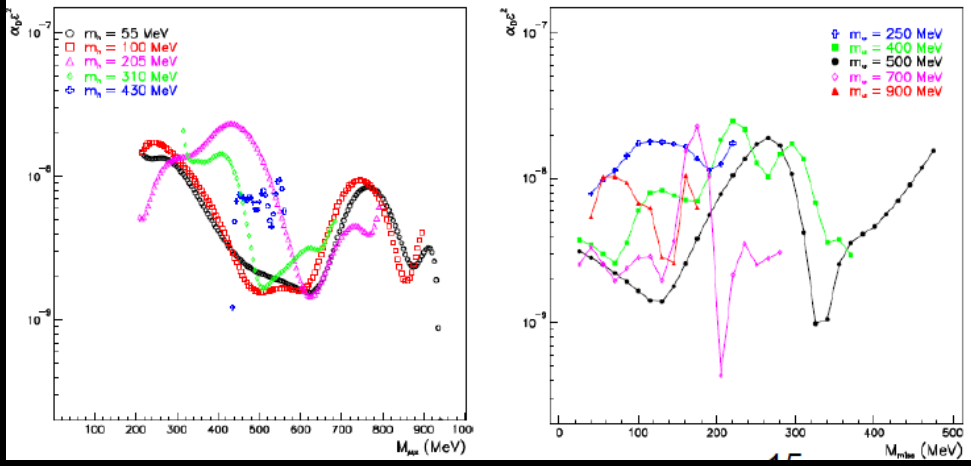
Belle II could improve by a factor 10-100 depending on the background level… if there is a light dark Higgs!

# Search for invisible decays of dark Higgs boson

F. Curciarello

## U boson searches @ KLOE: $e^+e^- \to h'U \to h'\mu^+\mu^-$




**Combined UL**
calculated by taking into account:
- the different integrated luminosities of the two samples
-different signal efficiencies and cross sections

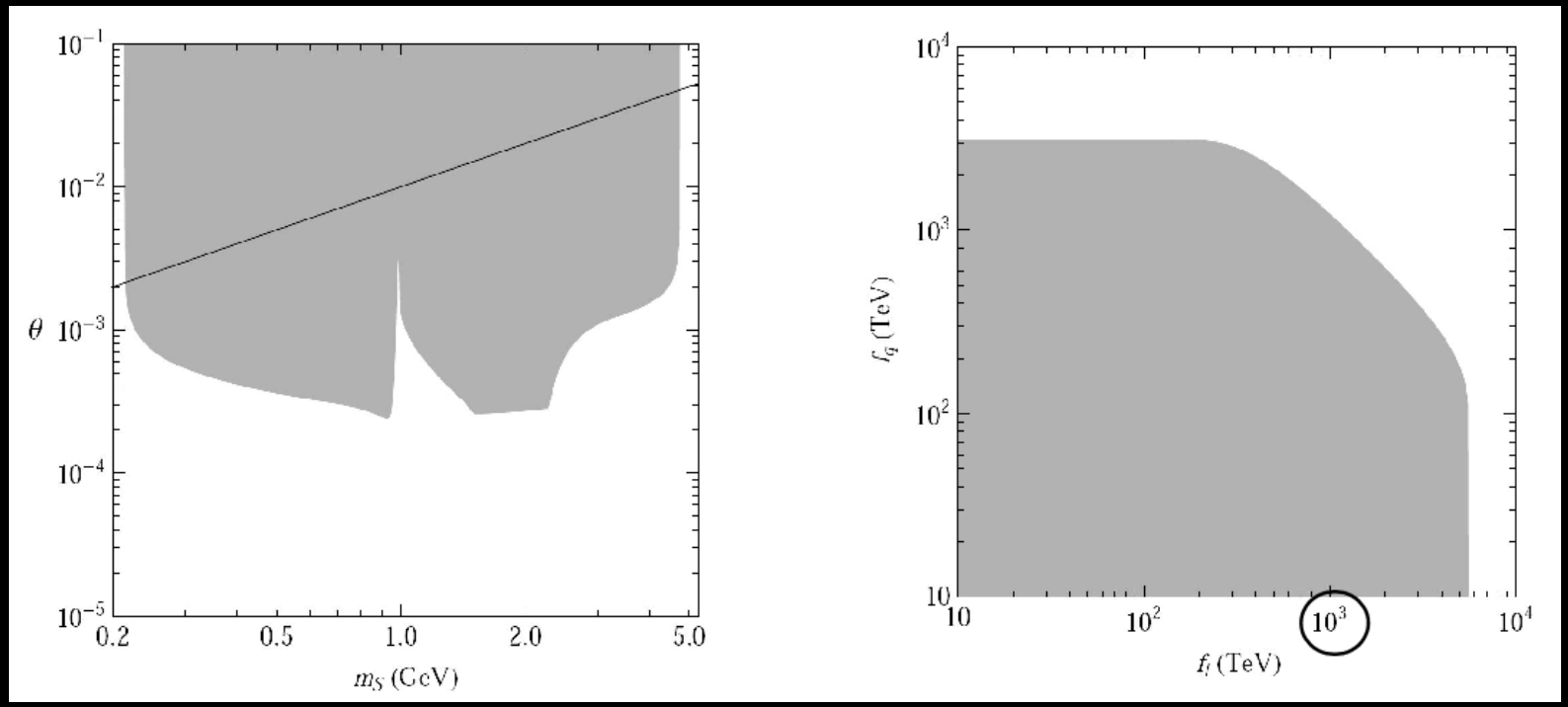
Values of order of $10^{-9} \div 10^{-8}$ in $\alpha_D \times \varepsilon^2$ are excluded at 90% CL for a large range of the dark photon and dark Higgs masses.

Factor 3-10 better at KLOE II, depending on background and luminosity

# Search for dark scalar / pseudoscalar

*Batell et al., PRD 83 (2010) 054005*

Expected limits for *BABAR* on scalar-Higgs mixing angle ($\theta$) and pseudo-scalar couplings ($f_{l,q}$) assuming limits on BF($B \rightarrow K^{(*)} l^+ l^-$ ) for a narrow $l^+ l^-$ (pseudo-)scalar at the level of ~$10^{-8}$




Limits on pseudo-scalar coupling at the level of thousands of TeV
Belle II could improve by an order of magnitude

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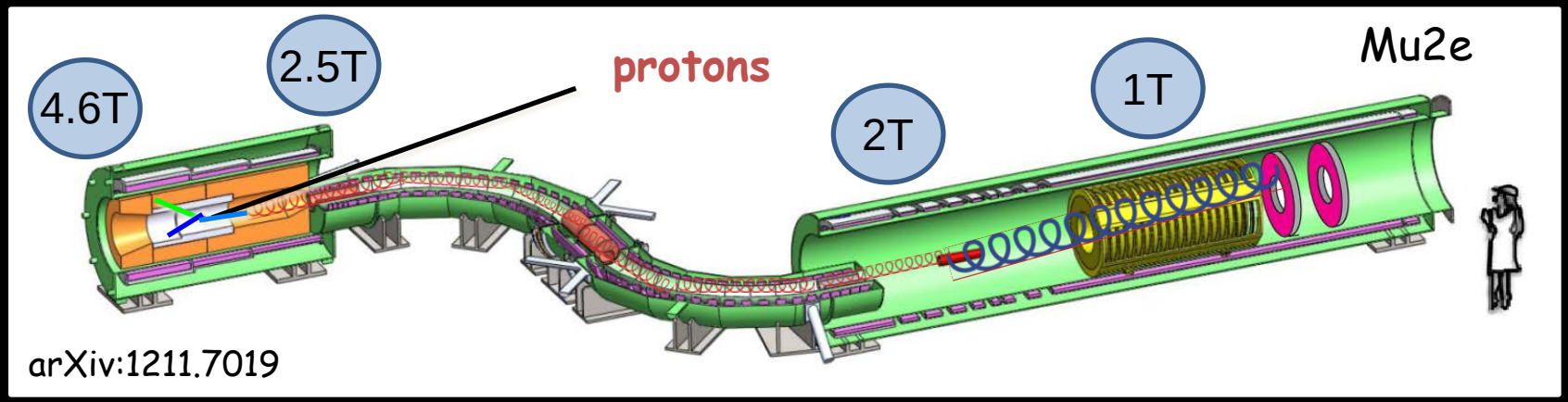
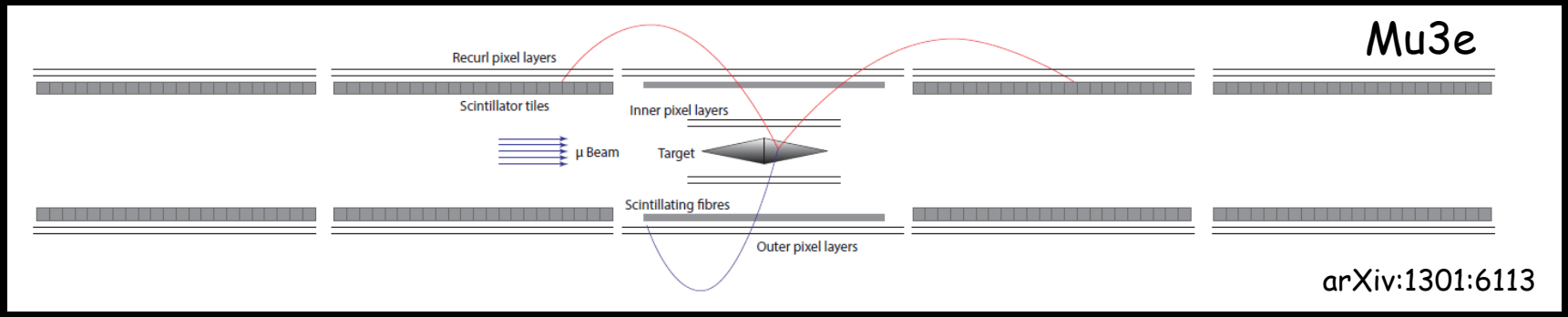
**+ related searches (hidden warped extra dimensions,...)**

# THE CRAZY STUFF

# Charged lepton flavor violation in muon decays

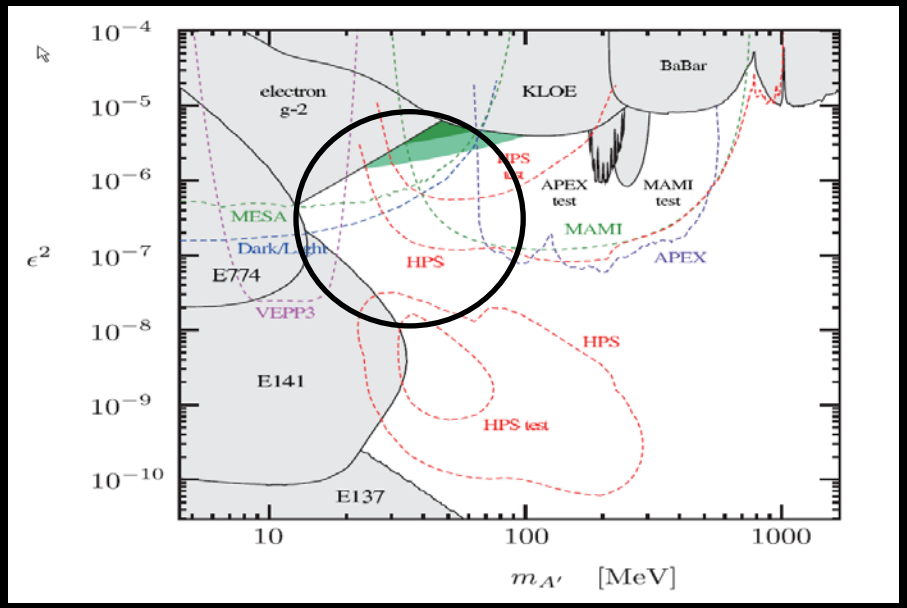
- Several experiments are planned to search for lepton flavor violation in muon decays
- Searches using $10^{15}$ or more muon decays (mu3e 2015+, Mu2e 2020+)



# Charged lepton flavor violation in muon decays

- Radiative muon decay BF ~ 1%. Also radiative pion decays.
- Could also produce dark photon, only costs a factor $\varepsilon^2$.
- Good detector to reconstruct $e^+e^-$ pair, with good efficiency.
- Can we explore the HPS island? Worth a quick study.



# Summary

- Future low-energy $e^+e^-$ colliders will collect much larger datasets than existing ones (~100x for Belle II w.r.t *BABAR*/Belle) and offer an improved sensitivity for hidden sector searches.

- Unique feature: can probe the structure of dark sector at $e^+e^-$ colliders: dark photon, Higgs, scalar, invisible decays,… , as well as scalar/pseudoscalar portal.

- Sensitivity to direct dark photon production ($e^+e^- \rightarrow \gamma A'$ , $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$) should increase by a factor 10 w.r.t limits from *BABAR*, reaching $\varepsilon^2 \sim 10^{-8}$. It seems difficult to go below.

- Similarly, the $e^+e^- \rightarrow \gamma\gamma$ backgrond might limit the reach for invisible decays.

- Might be worth to investigate reach using muon decays at CLFV experiments.